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F.C. Moon[2] and K. Hara[3]

Department of Theoretical and Applied Mechanics
Cornell University
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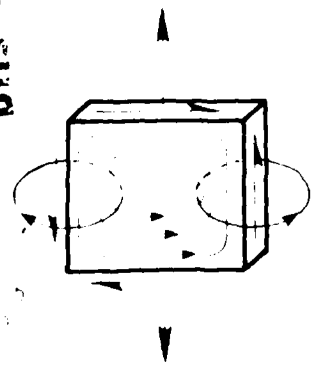
January 1980

Magnetomechanics Research



Departments of Theoretical & Applied Mechanics and Structural Engineering

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An experimental method is discussed for detecting vibrations of metal structures using magnetic fields. The theory assumes that the metallic structure acts as an antenna either through some small residual magnetization in ferromagnetic structures or through induced eddy currents. The detector consists of a noncontacting passive inductance coil.

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Detection of Vibrations in Metal Structures Using Small Passive Magnetic Fields

Introduction

Conventional methods of detecting structural motions include strain gages and accelerometers, which must be directly applied to the solid, and non-contacting devices such as capacitance, inductive and eddy current impedance detectors [1] which usually are placed in near contact with the solid (1 - 10 mm). There is interest however in determining the feasibility of structural motion detection far from the surface, say greater than 10 cm and perhaps as far as meters away without using active electromagnetic fields such as radar and lasers, etc.

In this short note, we explore the idea of using the vibrating structure as a transmitting antenna whose time varying magnetic fields can be detected by a passive inductance coil. In order for such a coil to produce a measurable voltage, the vibrating structure must produce a time varying magnetic field in the vicinity of the coil. There are a number of mechanisms by which this can be accomplished as summarized below.

i) Vibrating magnetic dipoles

If a material can retain some permanent magnetism (such as iron or steel) or has induced magnetism due to say the earth's magnetic field, then as the structure vibrates these moving dipoles will produce changing flux in the vicinity of the sensing coil. A diamagnetic material such as bismuth or a superconductor in a weak magnetic field can produce the same effect.

ii) Vibrating current carrying or induced eddy current conductors

If a structure is carrying current, the magnetic field associated with these currents will change when the structure vibrates. If there is no initial current in the conductor, circulatory currents (eddy currents) can be induced when the structure vibrates in a magnetic field with non-zero gradient. The associated time varying magnetic fields can be detected by a sensing coil.

iii) Magnetostriction effects

The change of magnetization in a ferromagnetic solid such as iron or steel can be effected by a change in strain (Matteucci-Villari effect [2]). Thus, even when the displacements of a structure are small, changes in stress due to vibration can change the local magnitude and direction of the magnetic dipoles in the strained solid. The resulting changes in magnetic field outside the body can be detected by a sensing coil.

iv) Barkhausen effect

Ferromagnetic materials are known to have a fine structure of magnetic domains or spin aligned regions. Changes in macroscopic magnetization are found to be a result of a realignment of these magnetic domains. The switching of spin alignment in domains has been found to be accompanied by a time varying magnetic field outside the solid which can be converted to voltage or audio signals (Barkhausen, see e.g. [2]). Thus vibration induced strains could initiate changes in domain alignment and produce a sequence of high frequency signals outside the solid.

v) Electron gas effect

A semi-classical model of elastic metallic conductor imagines a lattice of metal ions in a free electron gas. At low accelerations the electrons and ions move together thus producing zero net electric field outside the solid. However, at high frequencies, or high accelerations, the electrons and ions can have different motions and produce a net electric field outside the body [3],[4]. This effect has been observed [3] for torsional waves propagating in a rod. The conductor does not have to be ferromagnetic to exhibit this effect.

vi) Triboluminesence

Intense dynamic plastic strains in solids have been observed to produce measureable radiation outside the solid under impact type loads.

Of course similar phenomena occur in nonconductors such as piezoelectric and ferroelectric solids but we do not deal with structures of these materials in this note.

Theory - Ferromagnetic structures

A magnetized solid acts as a magnetic dipole which when vibrated produces time varying magnetic fields outside the solid. Far from the solid the dynamic signals behave as electromagnetic waves. However near the vibrating solid the magnetic fields behave as a quasistatic dipole field (or the sum of dipole fields). The magnetic dipole field is given by [6],

$$\underset{\sim}{B} = - \nabla U \tag{1}$$

where the magnetic potential for a point dipole of strength $\underset{\sim}{m}$ is given by

$$U = \mu_o \frac{\underset{\sim}{m} \cdot \underset{\sim}{r}}{4\pi r^3} \tag{2}$$

or

$$\underset{\sim}{B} = \frac{\mu_o}{4\pi} \left[\frac{-\underset{\sim}{m}}{r^3} + \frac{3(\underset{\sim}{m} \cdot \underset{\sim}{r})\underset{\sim}{r}}{r^5} \right] \tag{3}$$

where $\underset{\sim}{r}$ is the position vector from the dipole to the field point. When the structure vibrates both $\underset{\sim}{m}$ and $\underset{\sim}{r}$ will vary with time. If $\underset{\sim}{r}_o$ is the initial position and $\underset{\sim}{u}(t)$ the displacement of dipole then

$$\underset{\sim}{r}(t) = \underset{\sim}{r}_o + \underset{\sim}{u}(t) \qquad (4)$$

The magnetization can change magnitude as well as direction. If permanently magnetized then $\underset{\sim}{m}$ can change by the rotation vector of the dipole $\underset{\sim}{\Omega}(t)$ i.e.

$$\underset{\sim}{m}(t) = \underset{\sim}{m}_o + \underset{\sim}{\Omega} \times \underset{\sim}{m}_o \qquad (5)$$

The motions $\underset{\sim}{u}(t)$ and $\underset{\sim}{\Omega}(t)$ will generate a dynamic field, $\underset{\sim}{B}_1$, linear in $\underset{\sim}{u}$ and $\underset{\sim}{\Omega}$ and a non-linear contribution $B_2(t)$ such that

$$\underset{\sim}{B} = \underset{\sim}{B}_o + \underset{\sim}{B}_1(t) + \underset{\sim}{B}_2(t) \qquad (6)$$

where

$$\underset{\sim}{B}_1(t) = \left\{ \frac{\mu_o}{4\pi} \quad \frac{\underset{\sim}{m}_o \times \Omega(t)}{r_o^3} + \frac{3\underset{\sim}{r}_o(\underset{\sim}{r}_o \cdot \underset{\sim}{\Omega} \times \underset{\sim}{m}_o)}{r_o^5} \right. ,$$

$$+ \frac{3}{r_o^5} [\underset{\sim}{u}(\underset{\sim}{m}_o \cdot \underset{\sim}{r}_o) + \underset{\sim}{r}_o(\underset{\sim}{m}_o \cdot \underset{\sim}{u}) + \underset{\sim}{m}_o(\underset{\sim}{r}_o \cdot \underset{\sim}{u})]$$

$$\left. + \frac{15}{r_o^7} \underset{\sim}{r}_o \; (\underset{\sim}{m}_o \cdot \underset{\sim}{r}_o)\underset{\sim}{r}_o \cdot \underset{\sim}{u} \right\} \qquad (7)$$

The first two terms depend on $1/r_o^3$ while the next two terms depend on $1/r_o^4$. The dynamic field $\underset{\sim}{B}_1(t)$ is not only linear in $\underset{\sim}{\Omega}$ and $\underset{\sim}{u}$ but is also linear in $\underset{\sim}{m}_o$, the initial magnetization.

Many thin structures such as plates and shells have sharp edges which act as concentrators of magnetization. Thus for a plate with an edge concentration of magnetization $\underset{\sim}{m}_o$ per unit length along the x axis, integration of the field contribution of the dipoles along the edge considering the first term in $B_1(t)$ gives

$$\int_{-\infty}^{\infty} \frac{\underset{\sim}{m}_o \times \underset{\sim}{\Omega} \; dx}{(x^2+y^2+z^2)^{3/2}} = \frac{2\underset{\sim}{m}_o \times \underset{\sim}{\Omega}}{\rho_o^2} \qquad (8)$$

where $\rho_o = (y^2+z^2)^{1/2}$, (note $\underset{\sim}{m}_o$ and $\underset{\sim}{\Omega}(t)$ are assumed to be constant along the edge). We note further that for a plate or beam the rotation vector $\underset{\sim}{\Omega}$ is related to the lateral displacement of the plate $\underset{\sim}{u}$. Thus if a plate lies in the x-y plane

$$\underset{\sim}{u} = (0,0,w(x,y,t)) \tag{9}$$

and

$$\underset{\sim}{\Omega} = -\underset{\sim}{n} \times \nabla w$$

where $\underset{\sim}{n}$ is normal to the plate and ∇ is the divergence operator in the plane of the plate.

The time varying magnetic field can be detected using a passive multi-turn coil whose voltage output can be displayed graphically on an oscilloscope. The output voltage V is given by

$$V = N \frac{\partial}{\partial t} \Phi \tag{10}$$

where N is the number of turns and Φ is the dynamic flux given by

$$\Phi = \int_A (\underset{\sim}{B}_1 + \underset{\sim}{B}_2)\cdot\underset{\sim}{n}\, dA \tag{11}$$

where $\underset{\sim}{n}$ is normal to the coil area A bounded by the perimeter of the coil. We note that A is not unique but that Φ is independent of the choice of A.

If f is the frequency of the vibrating structure in hz., then the electromagnetic wavelength λ is given by

$$\lambda = c/f$$

where c is the speed of light.

The radiation terms contribute at distances $r_o \gg \lambda$ whereas for $r_o \ll \lambda$ the quasistatic field dominates. Note that for $f = 10^6$ hz.,

$\lambda = 300$ meters. This justifies the neglect of radiation terms for fields close to the structure.

Test Procedure

Ferromagnetic beams, plates and rods made from cold and hot rolled structural steel were vibrated in the earth's magnetic field and voltage measurements were made with a passive multi-turn search coil.

The sensing coil was wound from 0.05 mm (0.002 inch) diameter copper wire onto a 2.1 cm × 9.0 cm plastic coil form with 1000 turns. The coil had a resistance of 400 ohms and was connected to the amplifier of a storage oscilloscope which had an input resistance of 10^6 ohms and a maximum sensitivity of 1 mv per cm.

In almost all the experiments, free vibrationsof the flexible steel structures were generated by deflecting the beam or plate and suddenly releasing the structure.

One specimen was a cantilevered steel beam-plate 12.7 mm (0.5 inch) wide, 76.2 mm (3.0 inch) long, and 0.58 mm (0.023 inch) thick. This beam had a first mode natural frequency of 140 hz. Another large beam plate with lower frequencies also produced measureable voltages greater than one mv (45.7 cm × 3.81 cm × 1.59 mm).

Another specimen used was a solid steel rod of circular cross section (6.35 mm (0.25 inch) diameter) bent into a circular ring 23.5 cm (9.25 inches) in diameter. One quadrant of the ring was clamped which produced a fundamental frequency of vibration of 88 hz. Qualitative tests involving impact induced vibrations of a circular plate 54.6 cm (21.5 inches) in diameter and 1.27 mm (0.05 inch) thick were also conducted.

Voltage signals were also obtained from a vibrating aluminum plate 1.59 mm thick placed near a small 800 gauss permanent magnet.

Experimental Results

The small cantilevered beam-plate was first vibrated in a steady uniform magnetic field by placing the plate between the poles of a 10 cm diameter electromagnet. The magnetic flux lines were normal to the face of the beam. The induced voltage in the 1000 turn search coil as a function of applied magnetic field is shown in Figure 2. As one might expect, the output voltage is linear in the range from 100 - 400 gauss. The asymptotic voltage as $B \rightarrow 0$ is due to the residual magnetization in the steel plate itself. In this test the search coil face was parallel to and [illegible] cm from the beam-plate. The initial deflection of the beam was 2.3 mm (.09 inch).

The next series of experiments were conducted with the cantilevered beam out of the electromagnet in the earth's magnetic field (0.5 gauss). Three different residual magnetization values of the beam tip were used by magnetizing the plate; 15, 10, and 6 gauss at the tip of the beam. The search coil output voltage as a function of coil-beam distance is shown in Figure 3. The initial deflection was 6.34 mm (0.25 inch). Measureable voltages (0.1 mv) were observed at a distance of 10 cm. The coil face was again parallel to the beam face and perpendicular to the direction of vibration. No signals were obtained when the coil was rotated 90° or when its face was parallel to the direction of vibration.

The variation of output voltage as a function of distance is shown plotted on Log-Log scale in Figure 4. The behavior is of the form

$$V = K/x^n$$

where $1.5 < n < 1.9$. This is a smaller decrease than the simple theory would predict.

The variation of the residual magnetic flux normal to the face of the beam along the length of the beam is shown in Figure 5.

Another experiment was conducted with a solid steel rod bent into a circular ring. The free edges of the ring were clamped such that the ring could vibrate over 3/4 of its circumference. This test was conducted to eliminate the effect of the sharp edges which were present in the cantilevered plate. The ring had a residual magnetization on the outside surface of 7.5 gauss. The ring was vibrated normal to the plane of the ring. The search coil face was placed parallel to the plane of the ring directly over the circumference of the ring. The initial deflection of the ring was 8.6 mm. The output voltage as a function of coil-ring distance is shown in Figures 6, 7. The variation of voltage with distance appears to be similar to that predicted by simple theory, i.e.,

$$V = K/x^3 .$$

Oscillographs of the measured voltage signals are shown in Figure 8.

As indicated in the previous section voltage signals greater than 1 mv were measured at a distance of over 10 cm from a circular plate excited by impact. The signals show a broad spectrum of frequencies indicating that many modes were excited by the impact and were contributing to the change in magnetic field.

Finally qualitative tests on non-ferromagnetic plates were conducted by vibrating an aluminum plate near a small permanent magnet with a maximum field of 800 gauss. The magnet was placed about 5 cm from the plate. Vibrations evidently created eddy currents in the plate which produced measureable magnetic fields and voltages in a nearby search coil. No voltage was produced when a small cantilevered plate was placed in the uniform field of an electromagnet. This indicates that the generation of eddy currents in vibrating non-ferromagnetic conductors depends more on the field gradients of nearby sources of magnetic fields than on the absolute value of the magnetic field.

Future Work - Cryogenic Sensors

The ability to measure magnetic fields due to vibrating structures may be enhanced by using more sensitive magnetic field transducers. One method might be to use a mega-turn coil at cryogenic temperatures to lower the resistance. However the most sensitive method is the "Superconducting Quantum Interference Device" or SQUID, (see e.g. [7]). These devices are based on the Josephson effect and are capable of measuring magnetic field changes as low as 10^{-10} Tesla. Their drawback however is that at this extremely low sensitivity, other types of magnetic noise external to the vibration structure will be detected. Nonetheless it seems worth while to explore this technique for the detection of structural vibration.

Conclusions

1. Vibrations of ferromagnetic steel beams, plates and rings can be detected with a nearby passive search coil without external applied magnetic field.

2. The search coil voltage is inversely proportional to the distance raised to the power n, where $1.5 < n < 3.0$.

3. Maximum detection distances for 0.1 mv output were about comparable to the maximum dimension of the vibrating structure.

4. The coil output is maximum when the plane of the coil is normal to the direction of vibration of the structure.

5. It appears that the voltage will increase as the size of the vibration structure increases and as the frequency and amplitude of the vibration mode is increased.

6. Vibrations of non-ferromagnetic structures such as aluminum can be detected with a passive search coil if the structure vibrates in the magnetic field of a nearby magnet.

7. It would appear that the distance between sensor and vibrator could be easily increased by an order of magnitude by increasing the number of turns and area of the search coil, and using more sensitive amplifiers such as those employed in the study of geomagnetism.

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LIST OF FIGURES

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2. Search coil output voltage for a vibrating cantilevered steel beam-plate in an applied magnetic field.

3. Output voltage due to free vibrations of a cantilevered steel beam-plate with small permanent magnetization versus distance from the beam tip.

4. Search coil voltage versus distance for a freely vibrating cantilevered steel beam-plate. (Data for Figure 3 on Log-Log scale)

5. Distribution of magnetization along a steel beam-plate.

6. Search coil voltage for a vibrating steel ring of solid circular cross-section versus distance from the ring.

7. Data of Figure 7 on Log-Log scale.

8. Oscillographs of output voltage due to free vibration of steel structures.

FIGURE 1

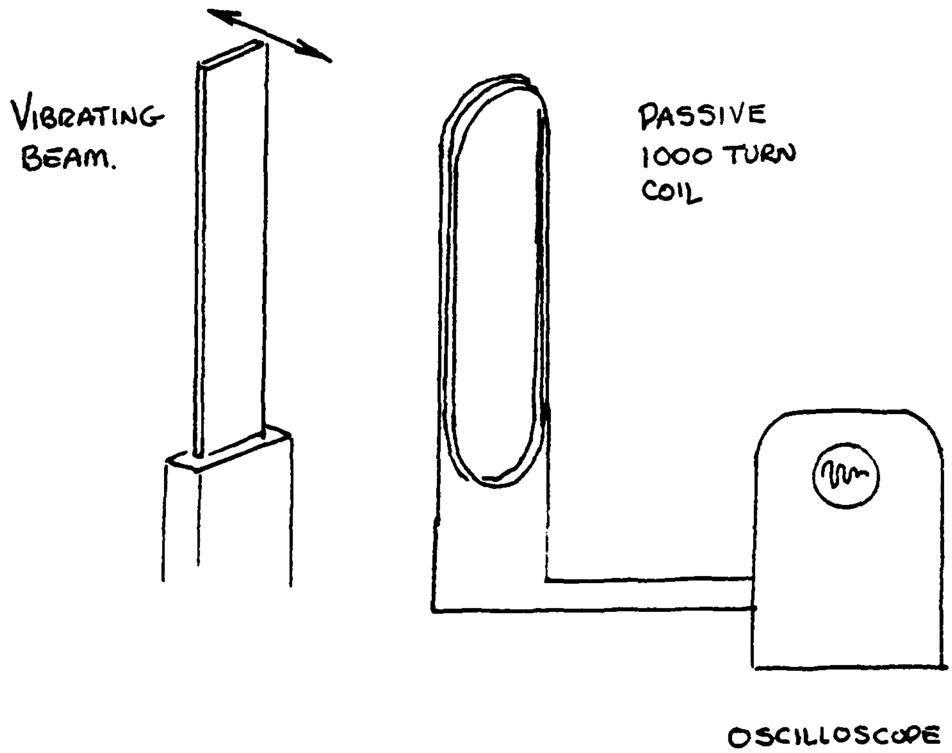
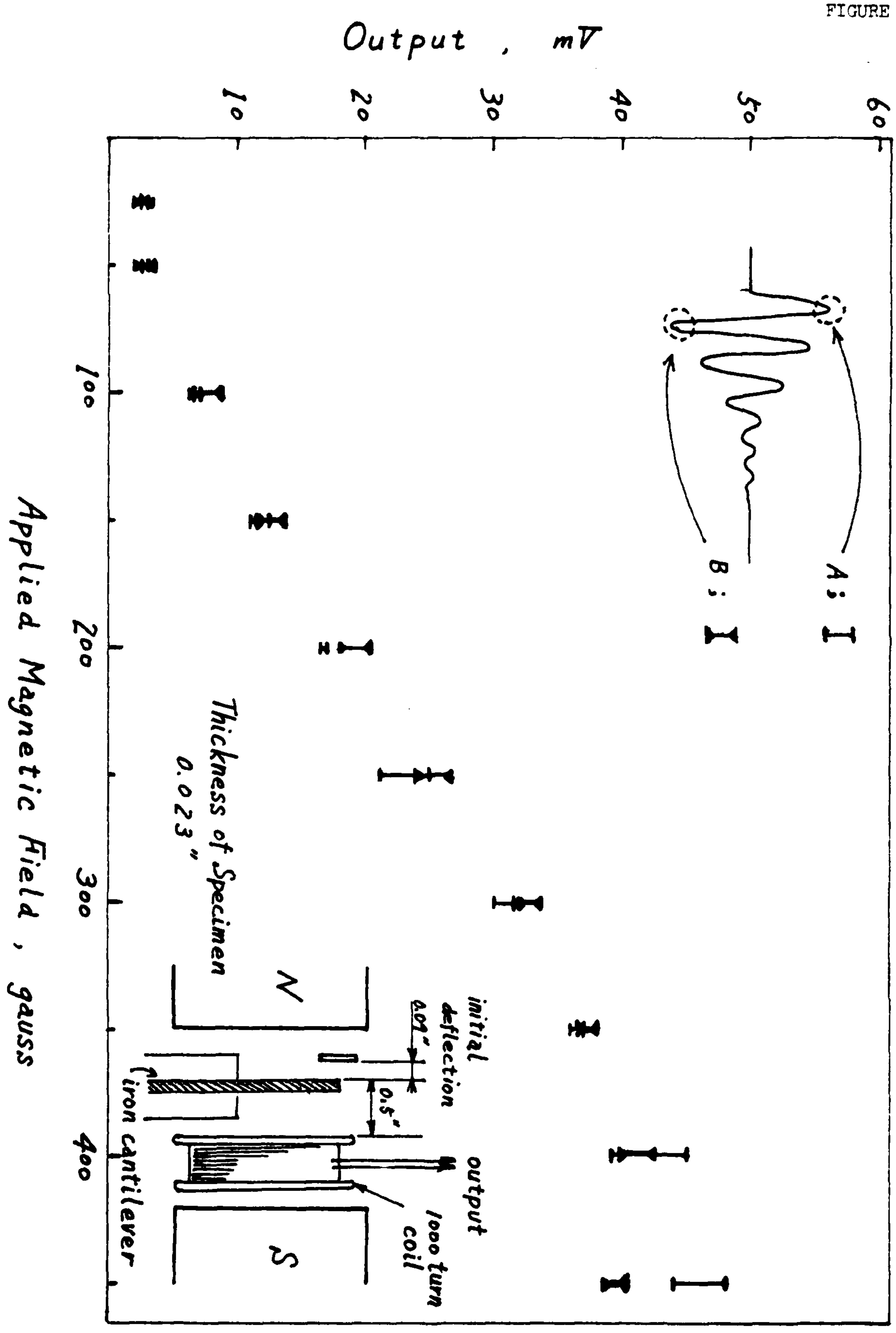
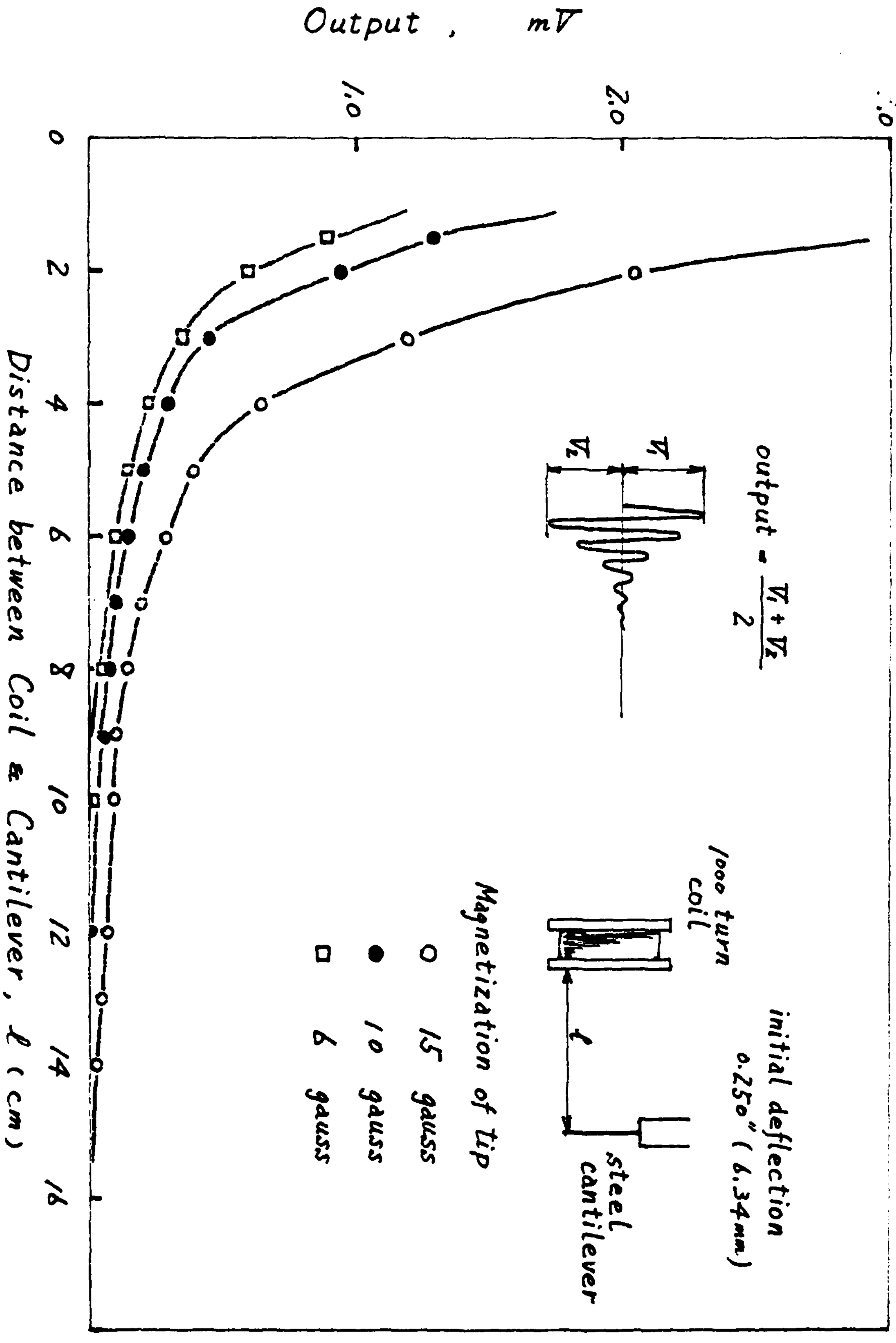


FIGURE 2



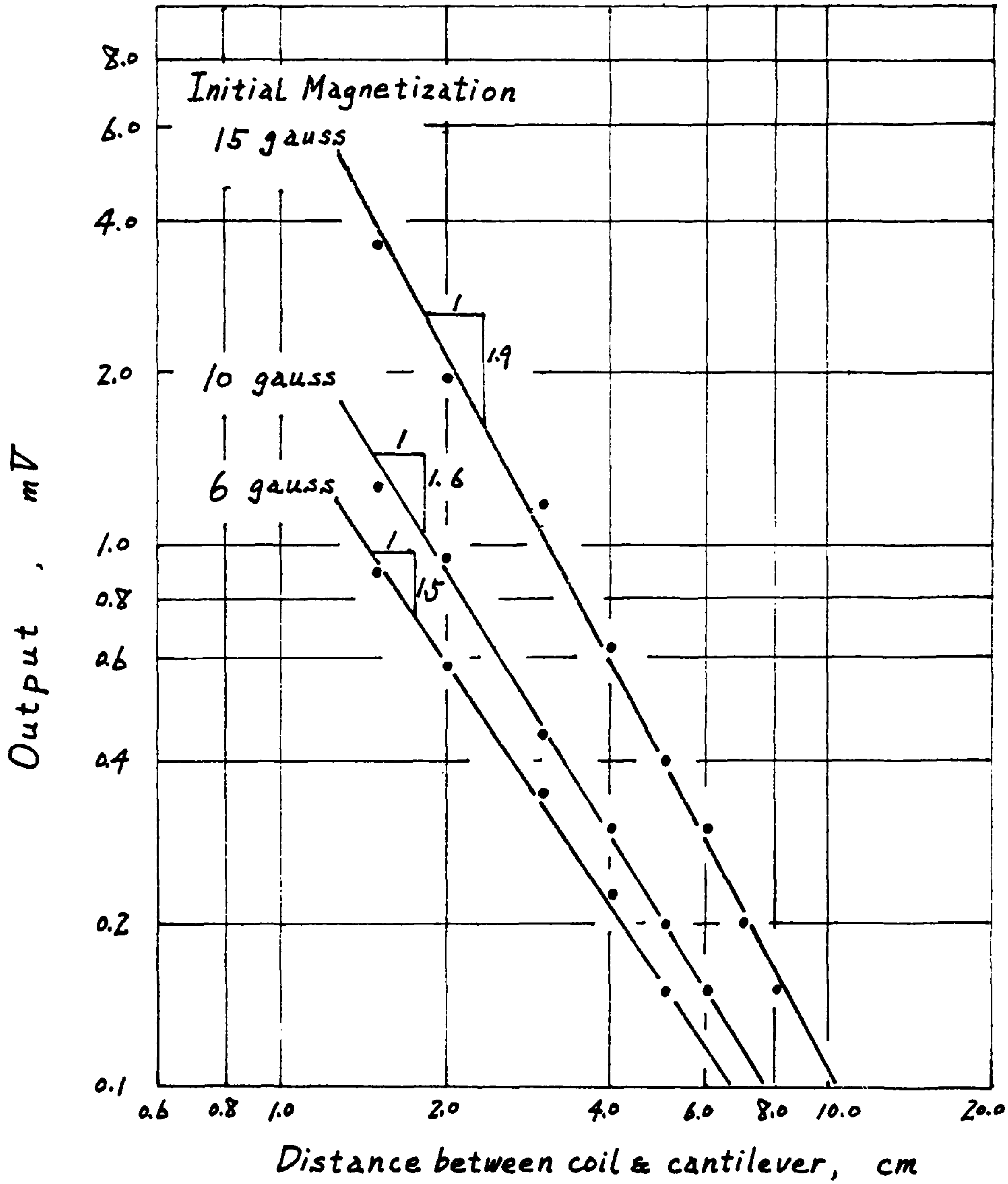
Output , mV
10
20
30
40
50
60
100
200
300
400
Applied Magnetic Field , gauss
A ;
B ;
Thickness of Specimen
0.023"
N
S
initial
deflection
0.01"
0.5"
output
1000 turn
coil
iron cantilever

FIGURE 3



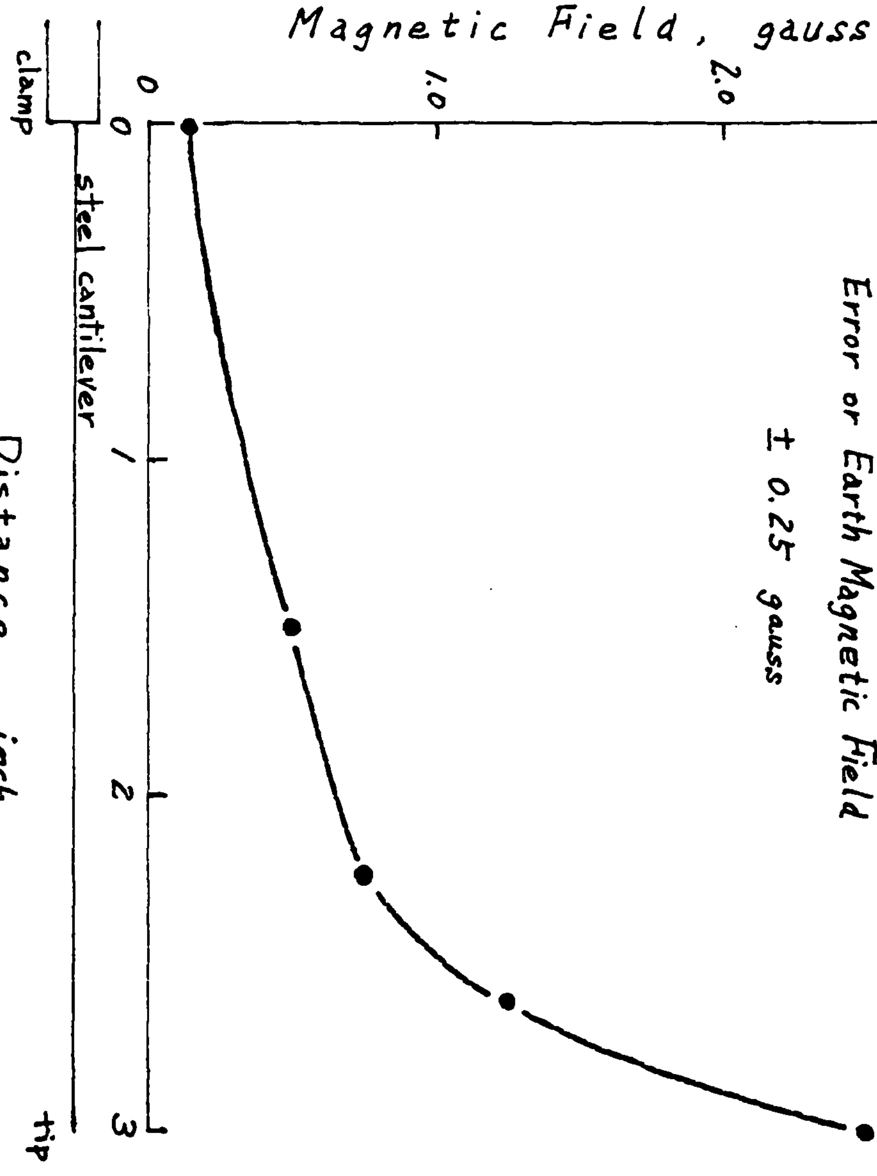
Output , mV
1.0
2.0
3.0
0
2
4
6
8
10
12
14
16
Distance between Coil & Cantilever, ℓ (cm)
output = (V1 + V2)/2
V1
V2
initial deflection
0.250" (6.34 mm)
1000 turn
coil
ℓ
steel
cantilever
Magnetization of tip
15 gauss
10 gauss
6 gauss

FIGURE 4



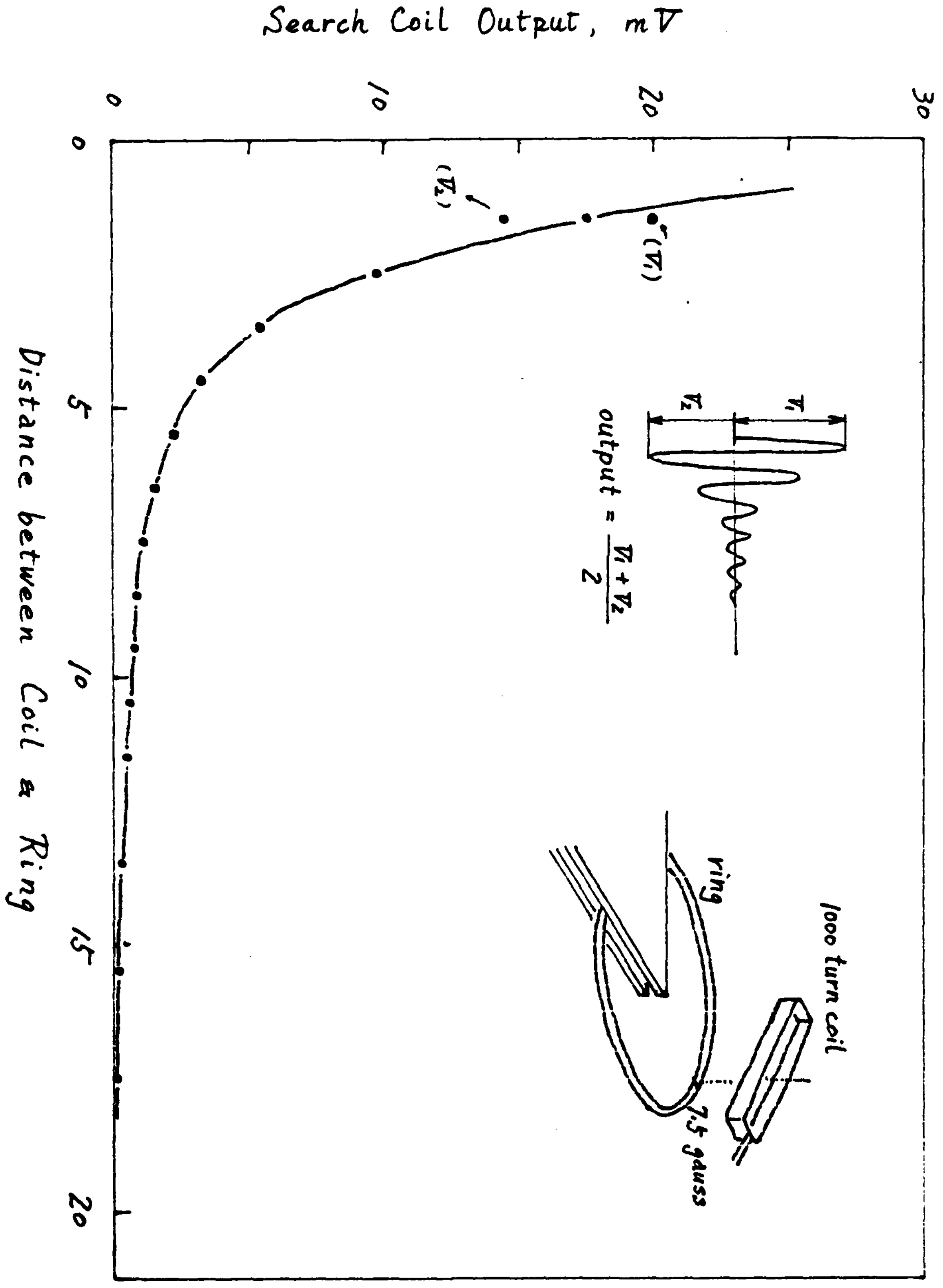
Initial Magnetization
15 gauss
10 gauss
6 gauss
1
1.9
1
1.6
1
1.5
8.0
6.0
4.0
2.0
1.0
0.8
0.6
0.4
0.2
0.1
0.6
0.8
1.0
2.0
4.0
6.0
8.0
10.0
20.0
Output , mV
Distance between coil & cantilever, cm

FIGURE 5



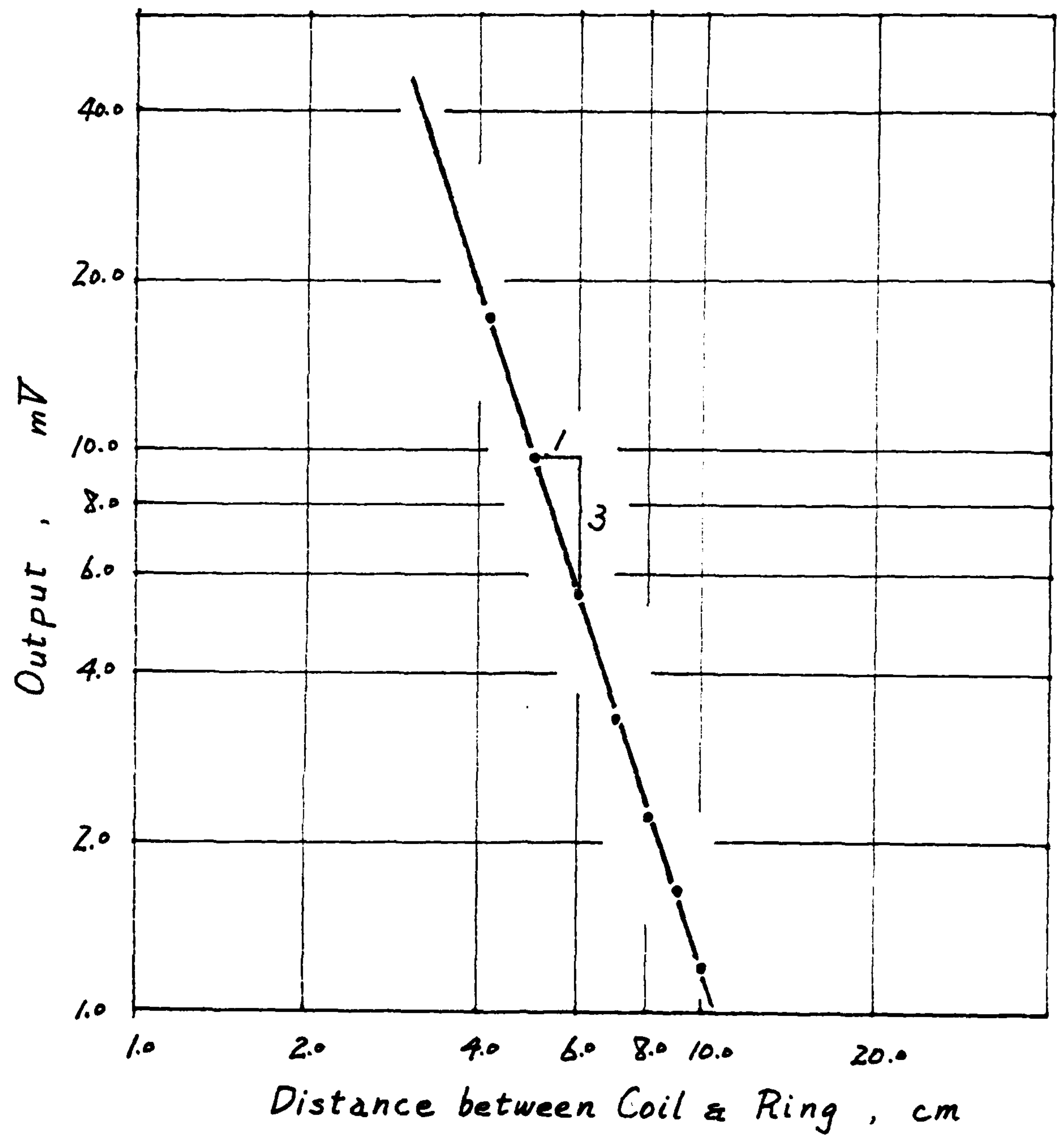
INITIAL MAGNETIZATION OF STEEL CANTILEVER NORMAL TO THE PLANE

FIGURE 6



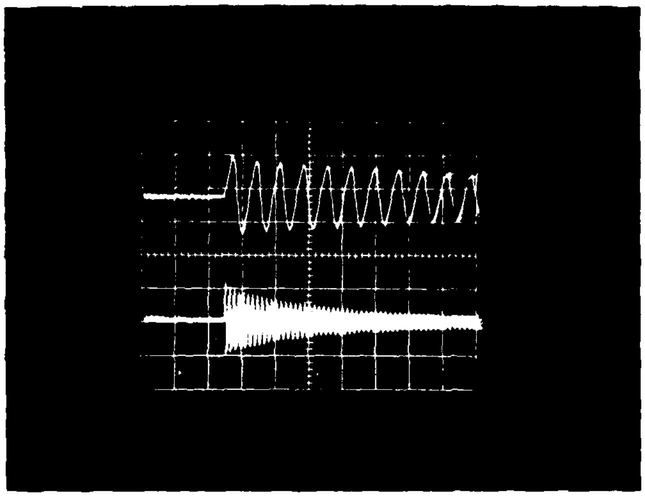
Search Coil Output, mV
0
10
20
30
Distance between Coil & Ring
0
5
10
15
20
(V_2)
(V_1)
V_1
V_2
output = $\frac{V_1 + V_2}{2}$
ring
1000 turn coil
7.5 gauss

FIGURE 7



40.0
20.0
10.0
8.0
6.0
4.0
2.0
1.0
Output , mV
1
3
1.0
2.0
4.0
6.0
8.0
10.0
20.0
Distance between Coil & Ring , cm

FIGURE 8



1 MV/DIV

10 MS/DIV

50 MS/DIV

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